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Single spin asymmetries in DIS

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Abstract:

We consider possible mechanisms for single spin asymmetries in inclusive Deep Inelastic Scattering (DIS) processes with unpolarized leptons and transversely polarized nucleons. Tests for the effects of non-zero intrinsic $\boldsymbol{k}_\perp$, for the properties of spin dependent quark fragmentations and for quark helicity conservation are suggested.

Single spin asymmetries in large p_T inclusive hadronic reactions are forbidden in leading-twist perturbative QCD, reflecting the fact that single spin asymmetries are zero at the partonic level and that collinear parton configurations inside hadrons do not allow single spin dependences. Similarly, one might expect single spin asymmetries to vanish in large angle and high energy exclusive processes. However, experiments tell us in several cases, both in inclusive [1, 2] and exclusive reactions [3], that single spin asymmetries are large and indeed non negligible.

The usual arguments to explain this apparent disagreement between pQCD and experiment invoke the moderate p_T values of the data – a few GeV, not quite yet in the true perturbative regime – and the importance of higher-twist effects. Several phenomenological models have recently attempted to explain the large single spin asymmetries observed in $p^\uparrow p \to \pi X$ [4]-[10], as twist-3 effects which might be due to intrinsic partonic $\boldsymbol{k}_\perp$ in the fragmentation and/or distribution functions. Single spin effects in exclusive processes are harder to explain, as one cannot rely on the cross-section factorization theorem, as one does in the inclusive case, but has to deal with helicity amplitudes; in particular one needs quite significant single helicity flip partonic amplitudes which, however, are bound to be of $\mathcal{O}(\alpha_s m_q/\sqrt{s})$ in pQCD, unless one resorts again to intrinsic $\boldsymbol{k}_\perp$ effects.

We consider here a process in which one has convincing evidence that partons and perturbative QCD work well and successfully describe the unpolarized and leading-twist spin data, namely Deep Inelastic Scattering (DIS). In particular we shall discuss single spin asymmetries in the inclusive, $\ell N^\uparrow \to \ell + jets$ and $\ell N^\uparrow \to hX$, reactions looking at possible origins of such asymmetries and devising strategies to isolate and discriminate among them.

According to the QCD hard scattering picture and the factorization theorem [11]-[13] the cross-section for the $\ell N^\uparrow \to hX$ reaction is given by

$$\frac{E_h\, d^3\sigma^{\ell+N,S\to h+X}}{d^3\boldsymbol{p}_h} = \sum_{q;\lambda_\ell,\lambda_q,\lambda'_q,\lambda_{q'},\lambda'_{q'},\lambda_h} \frac{1}{2}\int \frac{dx\, d^2\boldsymbol{k}_\perp d^2\boldsymbol{k}'_\perp}{\pi z}\frac{1}{16\pi x^2 s^2} \tag{1}$$
$$\rho^{q/N,S}_{\lambda_q,\lambda'_q}(x,\boldsymbol{k}_\perp)\, \tilde{f}^{N,S}_{q/N}(x,\boldsymbol{k}_\perp)\, \hat{M}^q_{\lambda_\ell,\lambda_{q'};\lambda_\ell,\lambda_q}\, \hat{M}^{q*}_{\lambda_\ell,\lambda'_{q'};\lambda_\ell,\lambda'_q}\, \widetilde{D}^{\lambda_{q'},\lambda'_{q'}}_{\lambda_h,\lambda_h}(z,\boldsymbol{k}'_\perp)$$

[wherever confusion is possible we label by q' the final quark, which is otherwise indicated by q].

Let us explain in some detail the meaning and physical content of the above equation. $\rho^{q/N,S}(x,\boldsymbol{k}_\perp)$ and $\tilde{f}^{N,S}_{q/N}(x,\boldsymbol{k}_\perp)$ are respectively the helicity density matrix and the total number density of quarks q with momentum fraction x and intrinsic transverse momentum $\boldsymbol{k}_\perp$ inside a polarized nucleon N with spin four-vector S. One can relate these quantities to the more familiar polarized structure functions; for example, for longitudinal polarization $S = S_L$ and in absence of intrinsic transverse motion, one has

$$\rho^{q/N,S_L}_{+,+}(x)\, f^{N,S_L}_{q/N}(x) = q_+(x)\,, \tag{2}$$

where + stands for $\lambda_q = 1/2$. In general $\rho^q_{\lambda_q,\lambda'_q}$ plays the same role as the density matrix of the initial state when describing a polarized scattering process [14].

$\widetilde{D}^{\lambda_q,\lambda'_q}_{\lambda_h,\lambda_h}(z,\boldsymbol{k}_\perp)$ describes the fragmentation process of a polarized quark q into a hadron h with helicity λ_h, momentum fraction z and intrinsic transverse momentum $\boldsymbol{k}_\perp$ with respect to the jet axis. It can be written in terms of the fragmentation amplitudes for the $q \to h + X$ process as

$$\widetilde{D}^{\lambda_q,\lambda'_q}_{\lambda_h,\lambda_h}(z,\boldsymbol{k}_\perp) = \sum\!\!\!\!\!\!\int_{X,\lambda_X} \mathcal{D}_{\lambda_X,\lambda_h;\lambda_q}(z,\boldsymbol{k}_\perp)\,\mathcal{D}^*_{\lambda_X,\lambda_h;\lambda'_q}(z,\boldsymbol{k}_\perp) \tag{3}$$

where the $\sum\!\!\!\!\!\!\int_{X,\lambda_X}$ stands for a spin sum and phase space integration of the undetected particles, considered as a system X. The usual unpolarized fragmentation function is simply

$$D_{h/q}(z) = \frac{1}{2}\sum_{\lambda_q,\lambda_h}\int d^2\boldsymbol{k}_\perp\,\widetilde{D}^{\lambda_q,\lambda_q}_{\lambda_h,\lambda_h}(z,\boldsymbol{k}_\perp)\,. \tag{4}$$

Finally the $\hat{M}^q$s are the helicity amplitudes for the elementary lepton-quark reactions; they depend on $x, \boldsymbol{k}_\perp$ and $\boldsymbol{k}'_\perp$ and their normalization is such that

$$\frac{1}{2}\,\frac{1}{16\pi x^2 s^2}\sum_{\lambda_\ell,\lambda_q,\lambda'_q}\hat{M}^q_{\lambda_\ell,\lambda_{q'};\lambda_\ell,\lambda_q}\,\hat{M}^{q*}_{\lambda_\ell,\lambda'_{q'};\lambda_\ell,\lambda'_q}\,\rho^{q/N,S}_{\lambda_q,\lambda'_q} = \frac{d\hat{\sigma}^{q,P_q}}{d\hat{t}}\,\rho^{q'}_{\lambda_{q'},\lambda'_{q'}} \tag{5}$$

where $d\hat{\sigma}^{q,P_q}/d\hat{t}$ is the cross-section for the $\ell q^\uparrow \to \ell q$ process, with an unpolarized lepton and an initial quark with polarization P_q described by $\rho^{q/N,S}$, and $\rho^{q'}_{\lambda_{q'},\lambda'_{q'}}$ is the helicity density matrix of the final quark q' produced in such a process. Then Eq. (1) can be written in a more intuitive way as

$$\frac{E_h\,d^3\sigma^{\ell+N,S\to h+X}}{d^3\boldsymbol{p}_h} = \sum_{q;\lambda_{q'},\lambda'_{q'},\lambda_h}\int\frac{dx\,d^2\boldsymbol{k}_\perp d^2\boldsymbol{k}'_\perp}{\pi z} \tag{6}$$
$$\tilde{f}^{N,S}_{q/N}(x,\boldsymbol{k}_\perp)\,\frac{d\hat{\sigma}^{q,P_q}}{d\hat{t}}(x,\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp)\,\rho^{q'}_{\lambda_{q'},\lambda'_{q'}}(x,\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp)\,\widetilde{D}^{\lambda_{q'},\lambda'_{q'}}_{\lambda_h,\lambda_h}(z,\boldsymbol{k}'_\perp)$$

where $\sum_{\lambda_{q'},\lambda'_{q'},\lambda_h}\rho^{q'}_{\lambda_{q'},\lambda'_{q'}}\widetilde{D}^{\lambda_{q'},\lambda'_{q'}}_{\lambda_h,\lambda_h}$ is simply the inclusive cross-section for the fragmentation process of the final polarized quark, $q' \to h+X$. Such expressions are in general not diagonal in the helicity basis; in the case where the final quark is unpolarized $\rho^{q'}_{\lambda_{q'},\lambda'_{q'}} = (1/2)\,\delta_{\lambda_{q'},\lambda'_{q'}}$ and one recovers the usual expression for the unpolarized cross-section. Notice that for helicity conserving elementary interactions $d\hat{\sigma}^{q,P_q}/d\hat{t}$ equals the unpolarized cross-section $d\hat{\sigma}^q/d\hat{t}$.

Similar formulae hold also when the elementary interaction is $\ell q \to \ell q g$ rather than $\ell q \to \ell q$: in the latter case two jets are observed in the final state – the target jet and the current quark jet – and in the former case three – the target jet and q + g current jets.

In Eqs. (1) and (6) we have taken into account possible intrinsic transverse momenta both in the distribution and the fragmentation process, together with a possible quark helicity non conservation in the elementary interactions (*e.g.*, $\lambda_q \neq \lambda_{q'}$). Parity conservation allows, in general, non-zero single spin asymmetries under reversal of the nucleon spin, $d^3\sigma^{\ell+N,S\to h+X} \neq d^3\sigma^{\ell+N,-S\to h+X}$, only for spin configurations with a non zero component perpendicular to the ℓh production plane; a spin orientation perpendicular to such a plane would maximize the magnitude of the asymmetry.

The $\boldsymbol{k}_\perp$ dependences are expected to have negligible effects on unpolarized variables for which they are indeed usually neglected, but they can be crucial for some single spin observables, as discussed in Refs. [4], [5], [10] and [11]; however, as a consequence of time reversal invariance, such effects cannot arise from the isolated process $p^\uparrow \to q+X$ (distribution function) or $q^\uparrow \to h+X$ (fragmentation function), but must involve some sort of initial state interactions between the proton and other particles in the reaction[1] or some final state interactions of the fragmenting quark. Such interactions are presumably always present in the case of fragmenting quarks; they are also expected, for the distribution functions, in some cases, *e.g.* in pp interactions, but should be of higher order in α_{em} and therefore negligible in DIS.

In the case $\ell N^\uparrow \to hX$ with the observation of target + current jets and eventually a final hadron inside a current jet one therefore remains with two possible theoretical sources of single spin asymmetries; in the quark fragmentation process and – perhaps more unlikely, but not impossible – in the elementary interactions. The former would confirm the suggestion of Collins [11], whereas the latter would test much more fundamental properties of DIS, namely helicity conservation of the elementary QED and QCD hard interactions and the factorization theorem, which are usually taken for granted, but are still in need of definitive confirmation.

We shall now describe a set of possible measurements which could shed light on and test the above mechanisms.

a) $\ell N^\uparrow \to \ell + 2\, jets$

Here one avoids any fragmentation effect by looking at the fully inclusive cross-section for the process $\ell N^\uparrow \to \ell + 2\, jets$, the 2 jets being the target and current ones; this is the usual DIS, the final quark spin is not observed, and one should set $\lambda_{q'} = \lambda'_{q'}$ so that Eq. (6) becomes

$$\frac{d^2\sigma^{\ell+N,S\to\ell+X}}{dx\, dQ^2} = \sum_q \int d^2\boldsymbol{k}_\perp\, \tilde{f}^{N,S}_{q/N}(x,\boldsymbol{k}_\perp)\, \frac{d\hat{\sigma}^{q,P_q}}{d\hat{t}}(x,\boldsymbol{k}_\perp)\,. \qquad (7)$$

In this case the elementary interaction is supposed to be a pure QED, helicity conserving one, $\ell q \to \ell q$, and $d\hat{\sigma}^{q,P_q}/d\hat{t}$ cannot depend on the quark polarization. Some spin dependence might remain in the distribution function, due to intrinsic $\boldsymbol{k}_\perp$ effects [4, 5, 10], but is expected to be of $\mathcal{O}(\alpha_{em})$. The observation of a non-zero single

[1] The possibility of spin-isospin interactions has also been recently suggested [15].

spin asymmetry in such a process would quite seriously – and utterly unexpectedly – question the degree of validity of the one photon exchange approximation in DIS and the QCD factorization theorem, which takes into account soft and collinear gluon emissions in the Q^2 dependent distribution functions.

b) $\ell N^\uparrow \to h + X \; (2\,jets,\; \boldsymbol{k}_\perp \neq 0)$

One looks for a hadron h, with transverse momentum $\boldsymbol{k}_\perp$, inside the quark current jet; the final lepton may or may not be observed. The elementary subprocess is $\ell q \to \ell q$ and Eq. (1) yields

$$\frac{E_h\, d^5\sigma^{\ell+N,S\to h+X}}{d^3\boldsymbol{p}_h d^2\boldsymbol{k}_\perp} = \sum_{q;\lambda_\ell,\lambda_q,\lambda'_q,\lambda_h} \frac{1}{2}\int \frac{dx}{\pi z}\frac{1}{16\pi x^2 s^2} \tag{8}$$
$$\times \quad \rho^{q/N,S}_{\lambda_q,\lambda'_q}\, f_{q/N}(x)\, \hat{M}^q_{\lambda_\ell,\lambda_q;\lambda_\ell,\lambda_q}\, \hat{M}^{q*}_{\lambda_\ell,\lambda'_q;\lambda_\ell,\lambda'_q}\, \tilde{D}^{\lambda_q,\lambda'_q}_{\lambda_h,\lambda_h}(z,\boldsymbol{k}_\perp)\,.$$

where we have neglected intrinsic $\boldsymbol{k}_\perp$ effects in the distribution functions, as they are expected to be of $\mathcal{O}(\alpha_{em})$. Eq. (8) is diagonal in the transverse spin basis and leads to the single spin asymmetry for transversely polarized nucleons:

$$\frac{E_h\, d^5\sigma^{\ell+N^\uparrow\to h+X}}{d^3\boldsymbol{p}_h d^2\boldsymbol{k}_\perp} - \frac{E_h\, d^5\sigma^{\ell+N^\downarrow\to h+X}}{d^3\boldsymbol{p}_h d^2\boldsymbol{k}_\perp} \tag{9}$$
$$= \quad \sum_q \int \frac{dx}{\pi z}\, \Delta_{_T} q(x)\, \Delta_{_N}\hat{\sigma}^q(x,\boldsymbol{k}_\perp)\, \left[\tilde{D}_{h/q^\uparrow}(z,\boldsymbol{k}_\perp) - \tilde{D}_{h/q^\uparrow}(z,-\boldsymbol{k}_\perp)\right]$$

where $\Delta_{_T} q$ is the polarized number density for transversely spinning quarks q and $\Delta_{_N}\hat{\sigma}^q$ is the elementary cross-section double spin asymmetry

$$\Delta_{_N}\hat{\sigma}^q = \frac{d\hat{\sigma}^{\ell q^\uparrow\to\ell q^\uparrow}}{d\hat{t}} - \frac{d\hat{\sigma}^{\ell q^\uparrow\to\ell q^\downarrow}}{d\hat{t}}\;\cdot \tag{10}$$

The quantity in square brackets on the r.h.s. of Eq. (9) could be non zero [11] and a measurement of the l.h.s. would be a clear test of such suggestion. Notice that even upon integration over $d^2\boldsymbol{k}_\perp$ the spin asymmetry of Eq. (9) might survive, due to some $\boldsymbol{k}_\perp$ dependence in $\Delta_{_N}\hat{\sigma}^q$: the original leading-twist Collins effect in the fragmentation will be diminished by $k_\perp/p_T$ higher twist terms and there might be cancellations between different quark contributions, but some overall effect might remain if one considers fast particles inside the current jets, so that only valence polarized quarks from the polarized nucleon contribute.

c) $\ell N^\uparrow \to h + X \; (2\,jets,\; \boldsymbol{k}_\perp = 0)$

By selecting events with the final hadron collinear to the jet axis ($\boldsymbol{k}_\perp = 0$) one forbids any single spin effect in the fragmentation process. As in the fully inclusive case *a*) the observation of a single spin asymmetry in such a case would require reconsideration of the degree of validity of the QED helicity conserving one photon exchange dominance and of QCD factorization theorem in DIS.

$d)$ $\ell N^\uparrow \to h + X$ $(3\,jets,\ \boldsymbol{k}_\perp \neq 0)$

The elementary process is now $\ell q \to \ell q g$ and one looks at hadrons with $\boldsymbol{k}_\perp \neq 0$ inside the q current jet. Single spin asymmetries can originate from the Collins effect in the fragmentation process, analogously to what was discussed in point $b)$.

$e)$ $\ell N^\uparrow \to \ell + 3\,jets$ or $\ell N^\uparrow \to h + X$ $(3\,jets,\ \boldsymbol{k}_\perp = 0)$

These cases are analogous to $a)$ and $c)$ respectively: the measurement eliminates spin effects arising from the distribution and fragmentation functions. The only possible origin of a single spin asymmetry would reside in the elementary interaction, which is now a hard perturbative QCD process, $\ell q \to \ell q g$. Single spin asymmetries require single quark helicity flip and the observation of such an asymmetry in this case would question quark helicity conservation, a fundamental property of pQCD which has never been directly tested.

In summary, a study of single transverse spin asymmetries in DIS could provide a series of profound tests of our understanding of large p_T QCD-controlled reactions[2].

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